CLPS 2022

Commercial Lunar Payload Services

Overnight Power & Thermal Solutions for Lunar Landers

Compass Team

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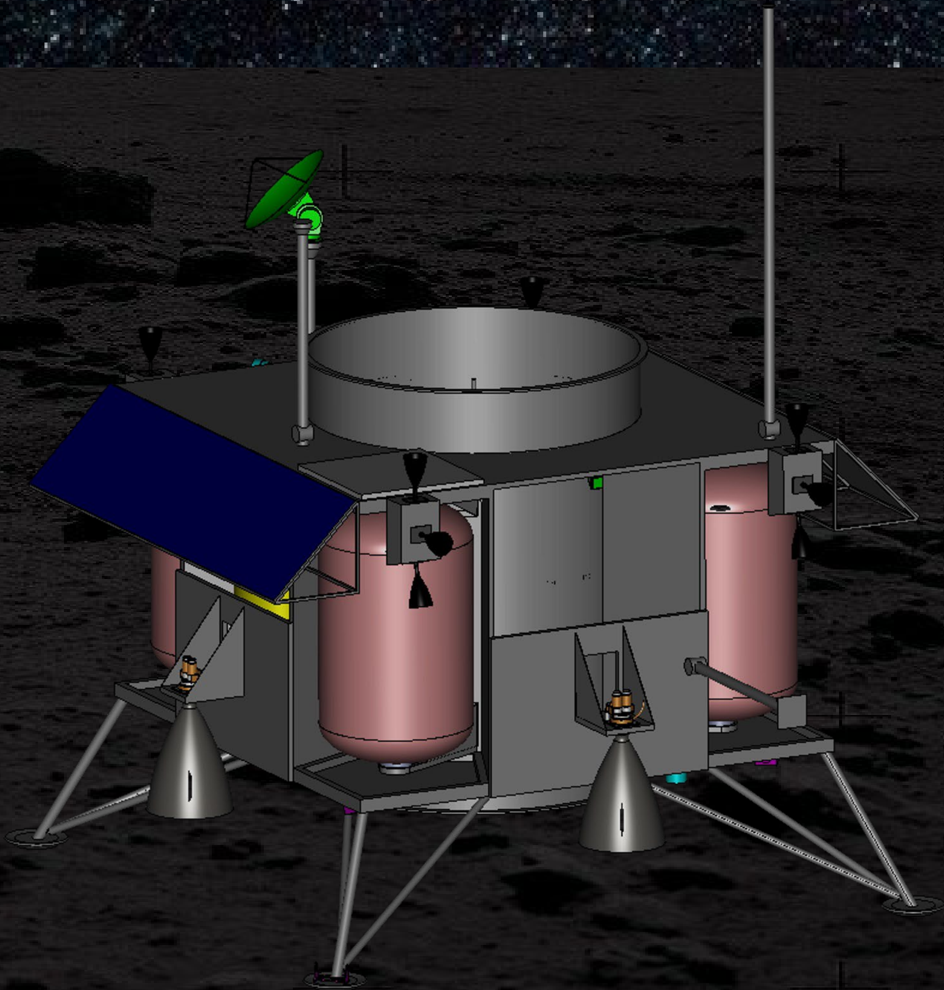
**NASA Glenn Research Center*

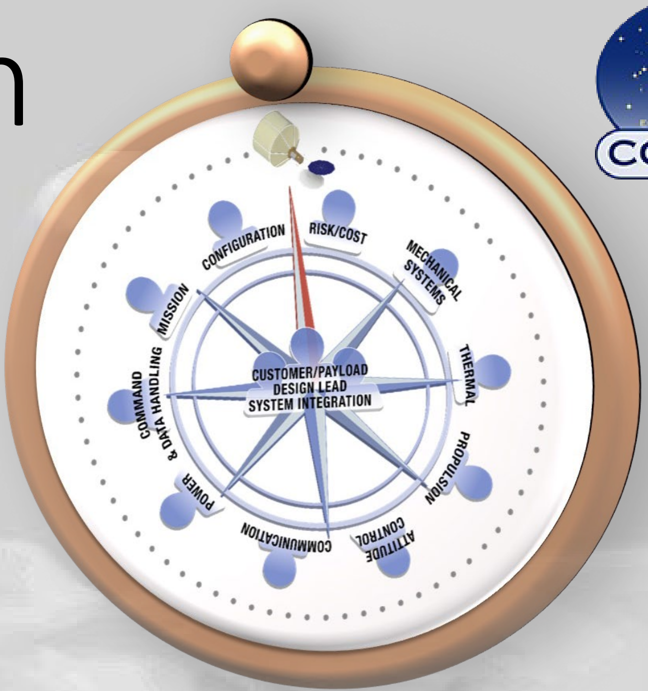
^HX5, LLC



Survive The Night Technology Workshop

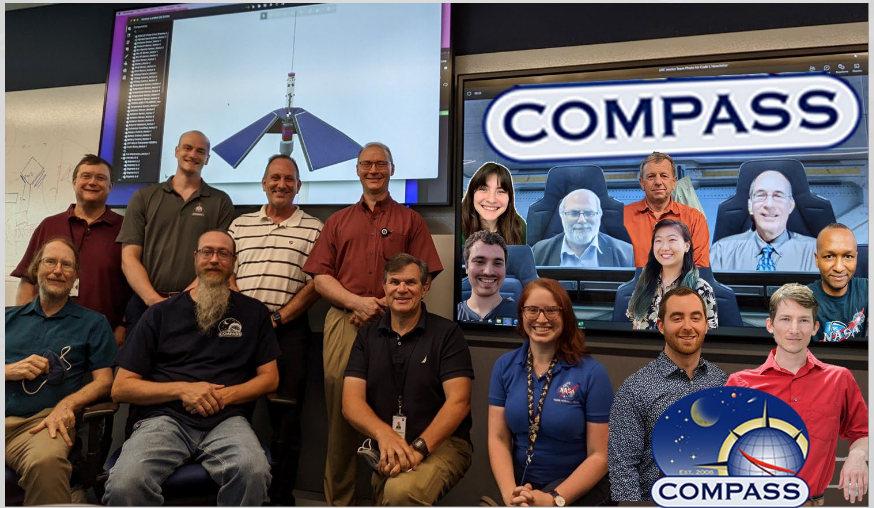
Dec. 6, 2022

Compass Team



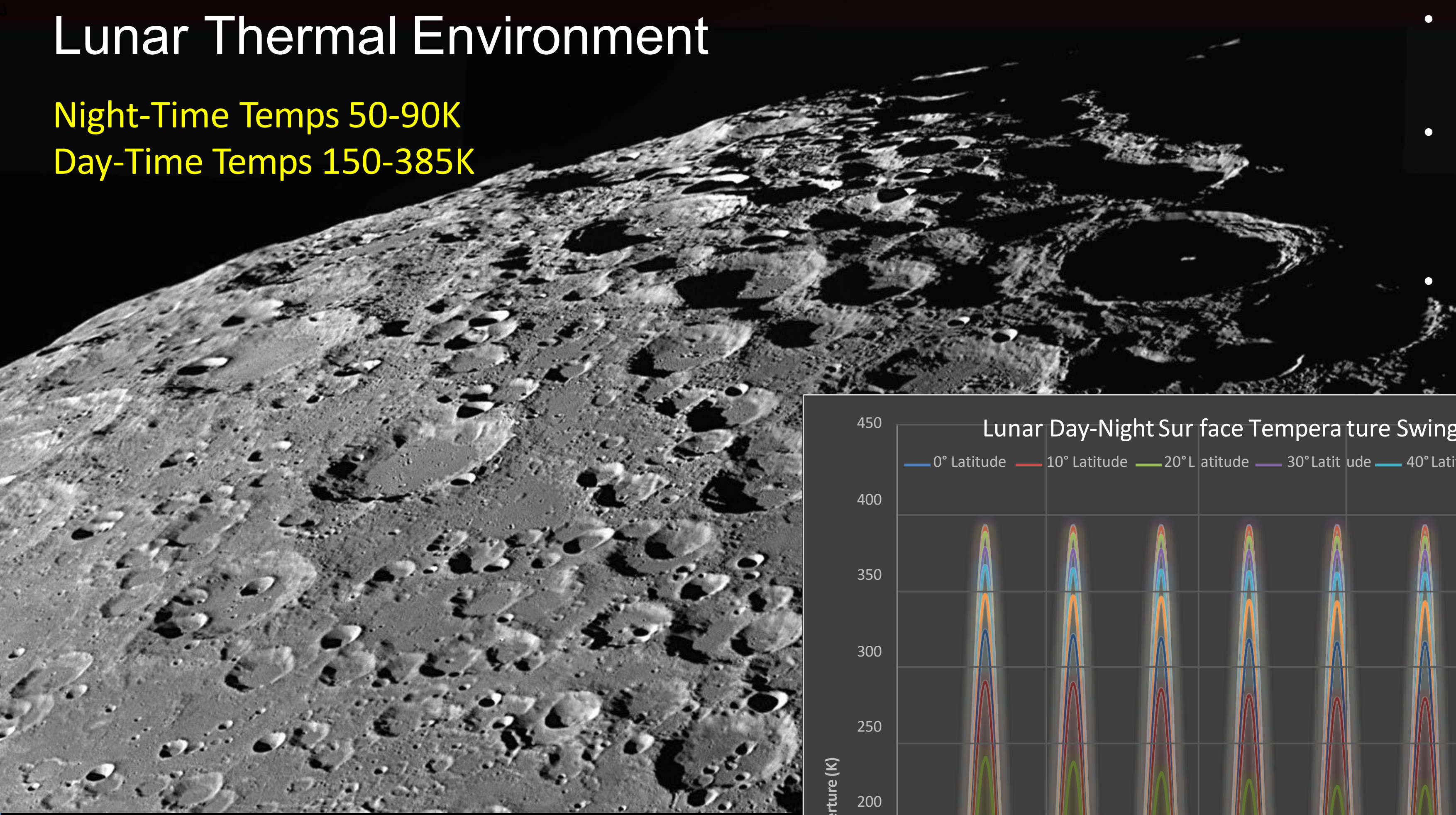
- The Compass concurrent engineering team was formed in 2006, and over 250 designs have been produced to-date
- The team includes experts from each discipline of space vehicle and mission design, collected from their respective discipline-area branches (matrix)
  – Branch knowledge and experience is leveraged through review of their representative's product(s)
- The experts are gathered in the Compass Lab and collaborate in real time to perform analyses. Includes capability to include remote members
- This approach results in quickly achieving high quality engineering designs without inefficiencies experienced by isolated teams

Please visit us in the Compass Lab during the Poster Session



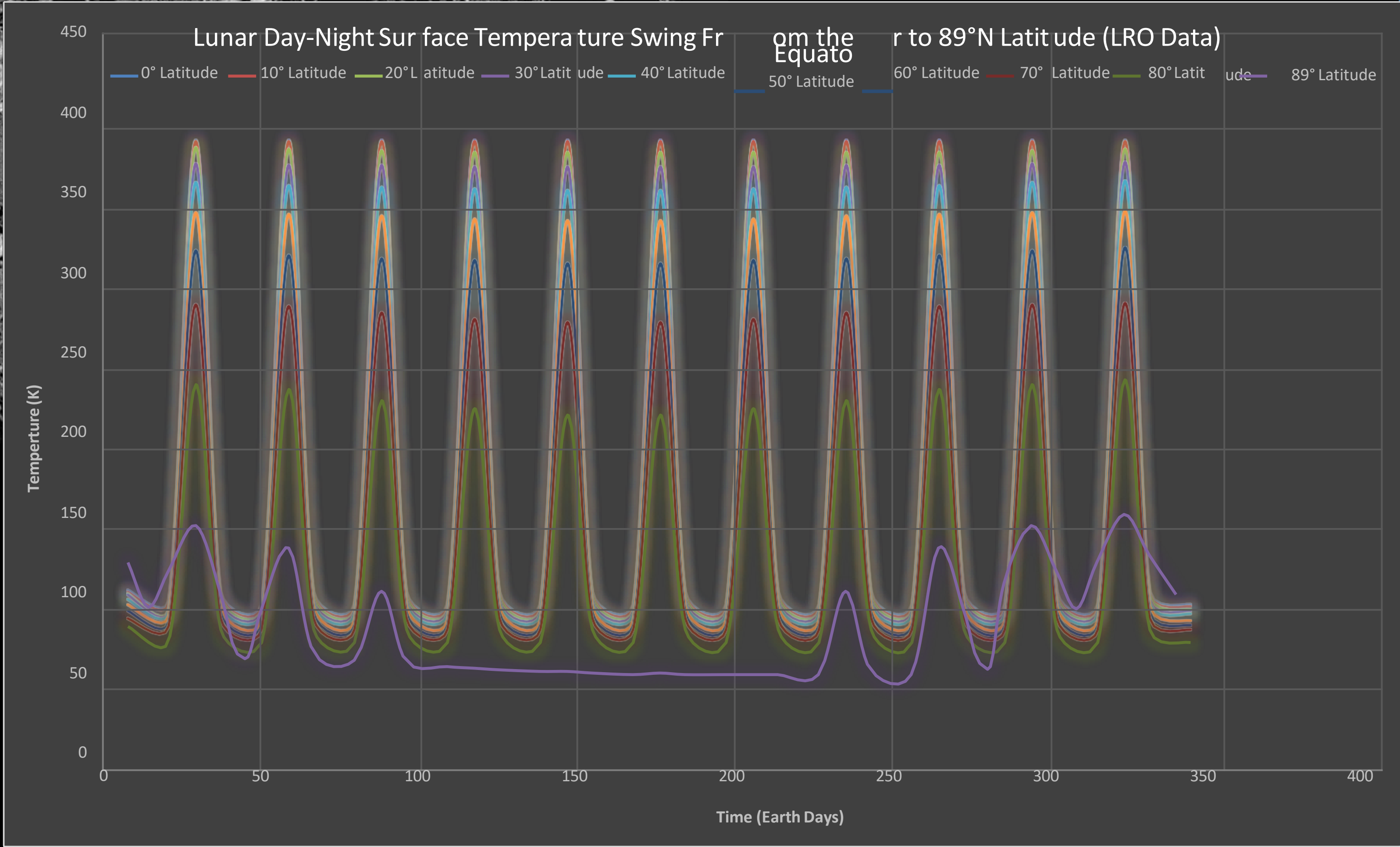
Recent Hybrid Compass Session (2-4 weeks long)

Lunar Thermal Environment



Night-Time Temps 50-90K
Day-Time Temps 150-385K

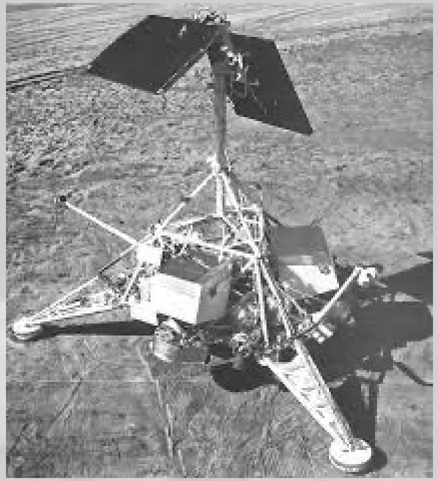
- During daytime operation near the equator the surface regolith will reach a temperature of ~385 K
- Nighttime temperatures at the equator are similar to those at other latitudes including the poles dropping below 100 K at nighttime.
- Due to the large temperature swings the equator has the worst operational thermal environment.

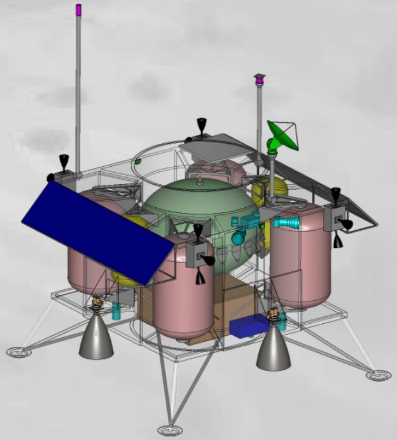


- The temperature curves for other Latitudes shows that the maximum surface temperature decreases as the latitude increase but the nighttime temperatures are similar at under 100 K
- The lower daytime surface temperature will make operation at these latitudes easier thermally than at the equator.

Lander Power and Thermal Solutions for the Lunar Night

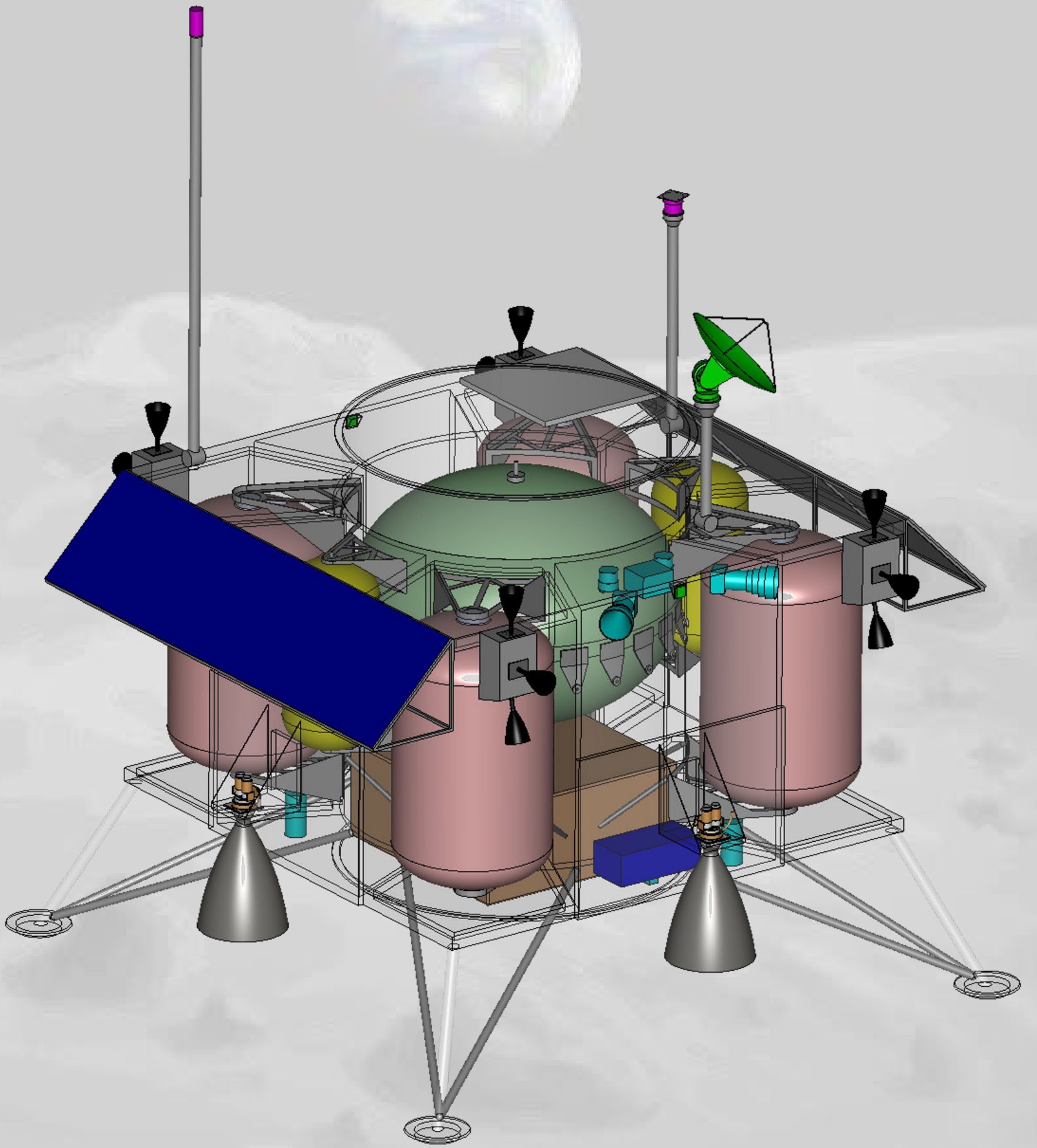
- ***Survive*** the Lunar Night
  - Surveyor landers ***survived*** lunar nights until equipment damaged
    - Had a much earlier class of electronics that could handle freezing better than some current IC devices
    - Batteries damaged
  - Much work is underway to develop/qualify electronics and energy storage to survive <80K lunar night temperatures
- ***Operate*** during the Lunar Night
  - While just surviving the lunar night allows for extended operations some missions like science, exploration, and ISRU require night-time operations; ***indeed operating during the lunar night would halve the time it takes to perform a mission***
- ***Two Recent Compass Designs explored Night Operations***
  - **Solar Array / Battery** and Thermal Vault approach for science collection during lunar night-time
  - **Radioisotope power** and heat source for Lunar Surface Relay operations





Generic Night-Time Science Lander

- Potential landing latitude ±45° latitude
- ~100 kg of science
  - Some on surface and subsurface
- >5 year life
- Night-time power reqt's ~ 40W



Power Source, Storage, Thermal Trades

Study focused on impact of not using radioisotopes

Lunar Night Approach Trade

Components for the Lunar Night

1. **All lander Subsystems/Payload kept > -40C**

Big Battery: Requires large, heavy batteries and Larger Solar arrays

Heaviest option

2. **Subset of Instruments and dedicated support equipment kept >-40C**

Stand-alone Lunar night Systems: Requires additional but smaller payload support equipment (C&DH, comms, power)

Lighter than option 1. ? but may be more expensive due to adding components

Reuse of Some Lander systems: Nighttime payload and data controller kept >-40C, Mix of reusing lander subsystems that can survive night and dedicated nighttime systems

Assumes comms, solar arrays, and daytime only science probes (not science electronics) be allowed to freeze during the night

Thermal Vault approach chosen for this study

Systems and the Lunar Day/Night

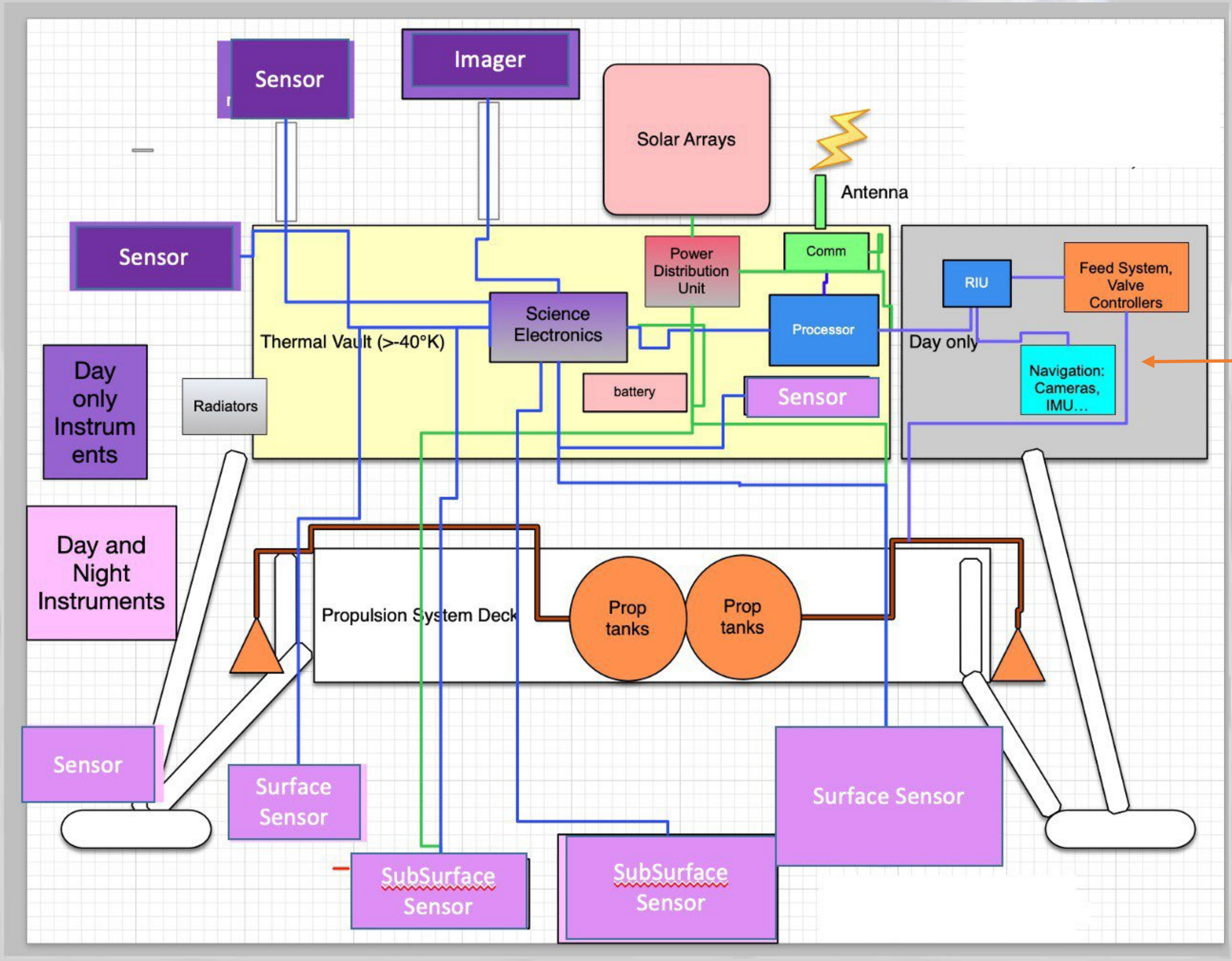
(equatoria to 45° latitude)

Subsystem	Sub-Elements Exposed to Lunar Day/Night (400K/80K)	Sub-Elements Protectable in a thermal Vault Day/Night (55C to -40C)
Science	Sensors (some on or below surface), Actuators, power/data lines	Electronics/controllers
Power	Solar Arrays, power lines to users	Batteries, PMAD
Communications	Antennas, gimbals	Transceivers, Switches….
C&DH	Data/Control lines to users	Computers, controllers, Data storage
Thermal	Radiators	Heaters, RHUs
Propulsion	Thrusters/Valves/ Feed Sys	Lines to power/Controllers
GN&C	Landing Sensors, Star trackers…	IMUs, lines to sensors

Assumed some external components (science sensors, cameras, comm antennas/gimbals…) can survive the lunar night

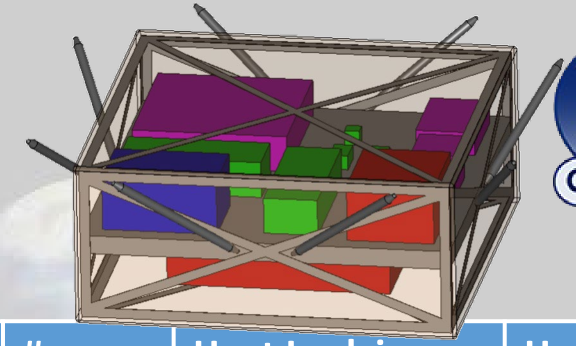
Schematic

- External Power/Data/Control Connections from Thermal Vault
  - Science
    - Beneath Surface (3)
    - On surface (5)
    - On deck (5)
  - Comms Antenna
  - Solar Arrays
  - Radiators
  - Nav cameras, star-trackers (2)
  - Feed System, Actuators
  - Structure



Approach put 'lander only' (propulsion and Attitude Determination and Control) Controllers outside of thermal vault in order to reduce vault size and number of heat leaks

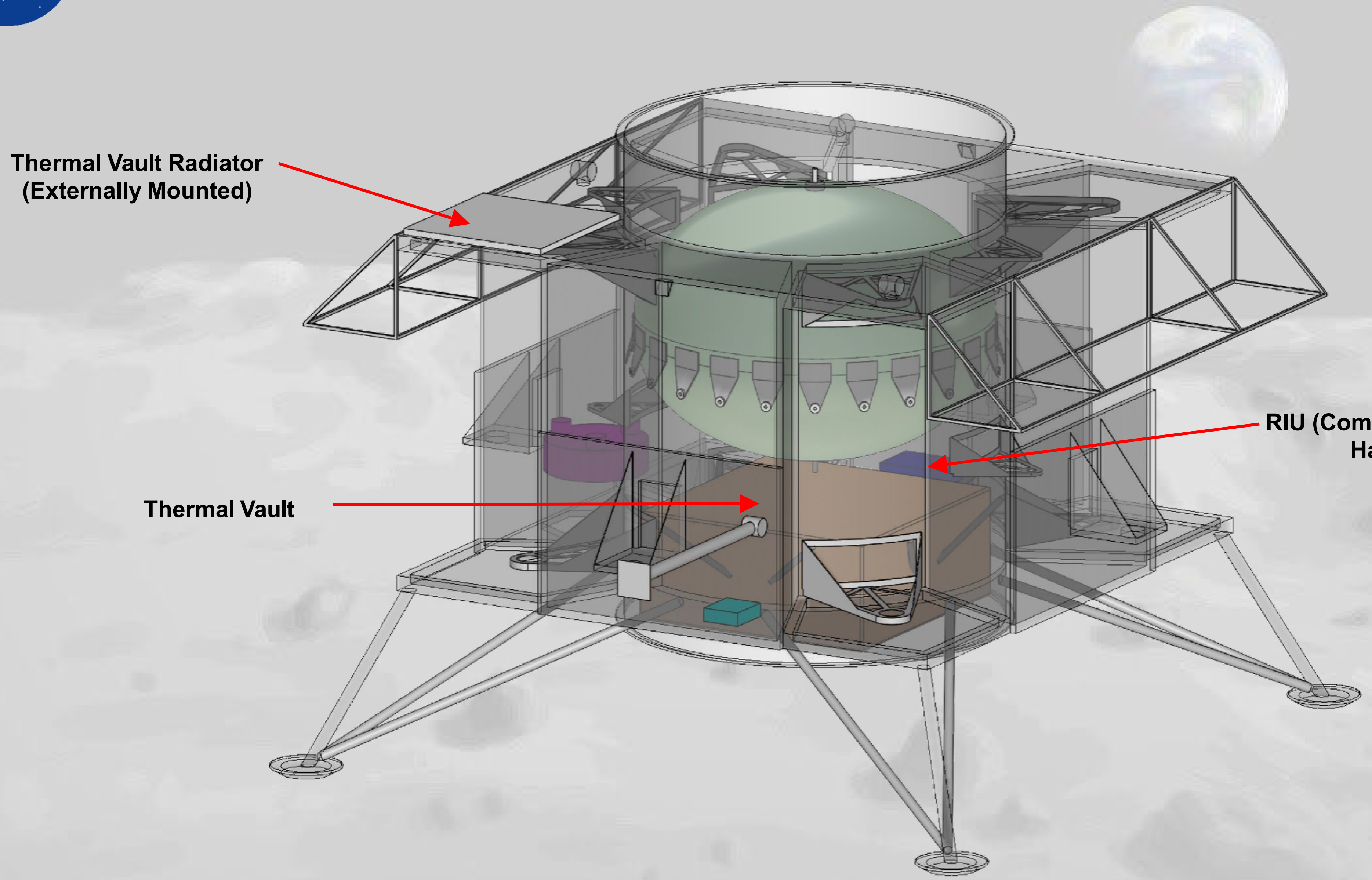
Heat Leak Summary for Thermal Vault



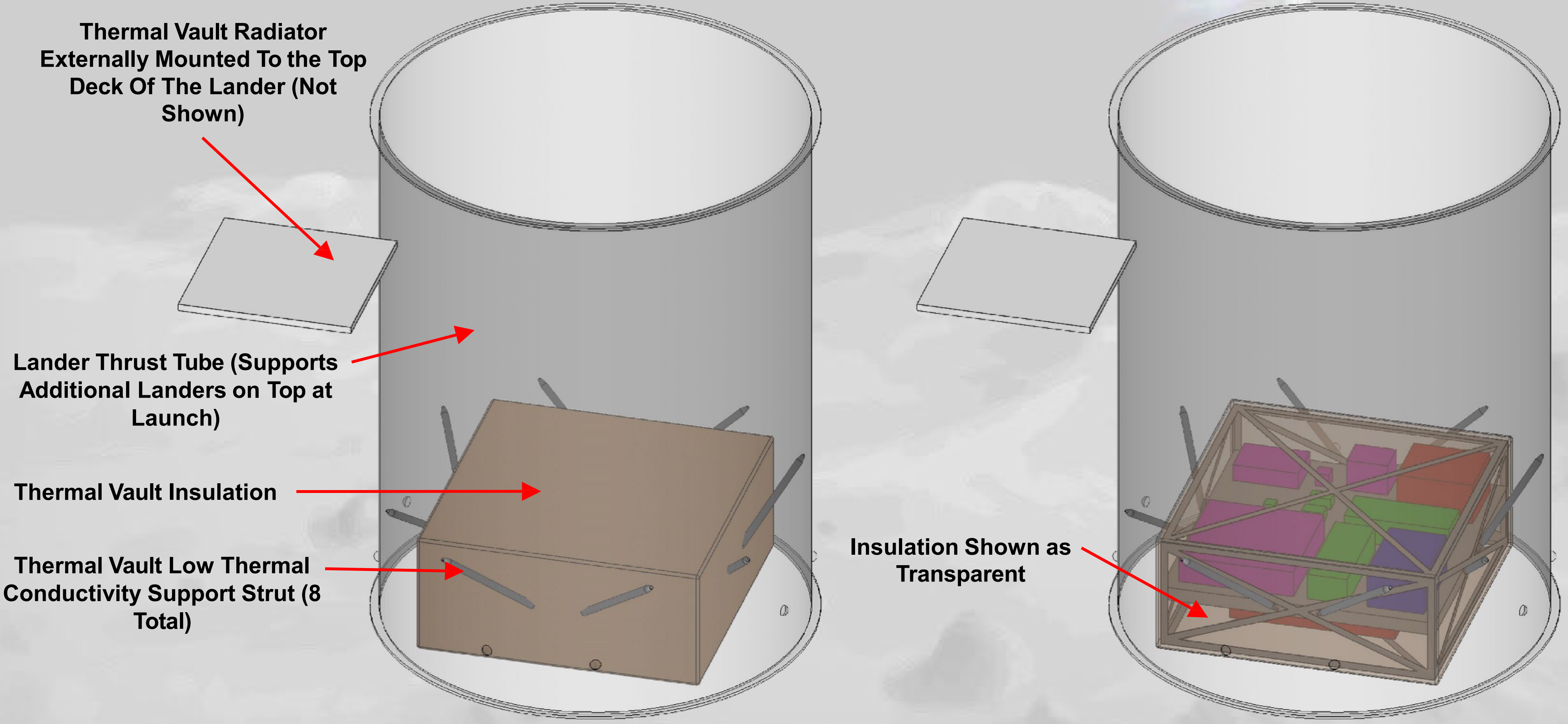
Daytime: Operating Temperature: 323 K, Sink Temperature: 354 K
Nighttime: Operating Temperature: 250 K, Sink Temperature: 64 K

Item	Dimensions	Material	Thermal Conductivity	Insulated Length	#	Heat Leak in during the Day	Heat Loss out at Night
Insulation (direct heat loss)	Surface Area 4.08 m^2	Aluminized Mylar	0.0009 W/mK (effective)	NA	25 Layers	0.7 W	0.8 W
Insulation Seams and Passthrough Heat Loss	**Surface Area ~4 m^2, with 5% seam and passthrough effected area**	**Aluminized Mylar**	**0.0009 W/mK (effective)**	**NA**	**25 Layers**	**8 W**	**9.4 W**
Structure Standoffs	OD: 1.5 cm, Wall 0.5 cm	S-Glass Composite	0.75 W/mK	0.95 m	8	0.01 W	0.19 W
Power In Wires	**Diameter 0.8 mm (20 gauge)**	**Copper**	**401 W/mK**	**1 m**	**40**	**0.8 W**	**1.5 W**
Data Wires	**Diameter 0.8 mm (20 gauge)**	**Aluminum**	**177 W/mK**	**1 m**	**116**	**1.0 W**	**1.9 W**
Power Out Wires	**Diameter 1.36 mm (16 gauge)**	**Copper**	**401 W/mK**	**1 m**	**2**	**0.1 W**	**0.6 W**
Heat Pipes	OD: 1 cm, Wall 0.5 mm	Titanium	6.7 W/mK	0.5 m	8	0.15 W	0.3 W
					Total	**10.53 W**	**14.69 W**

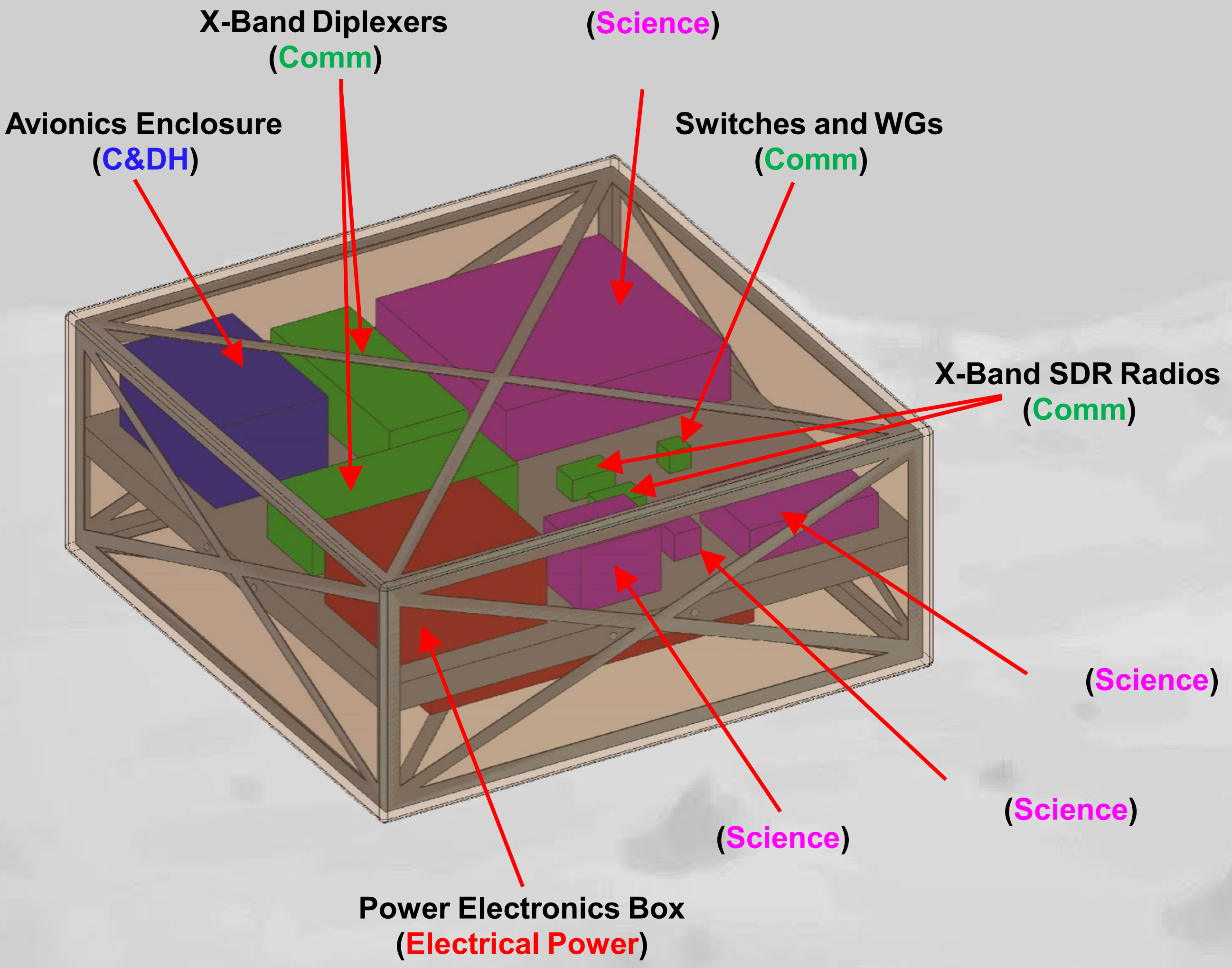
Lunar Night Lander Internal Components

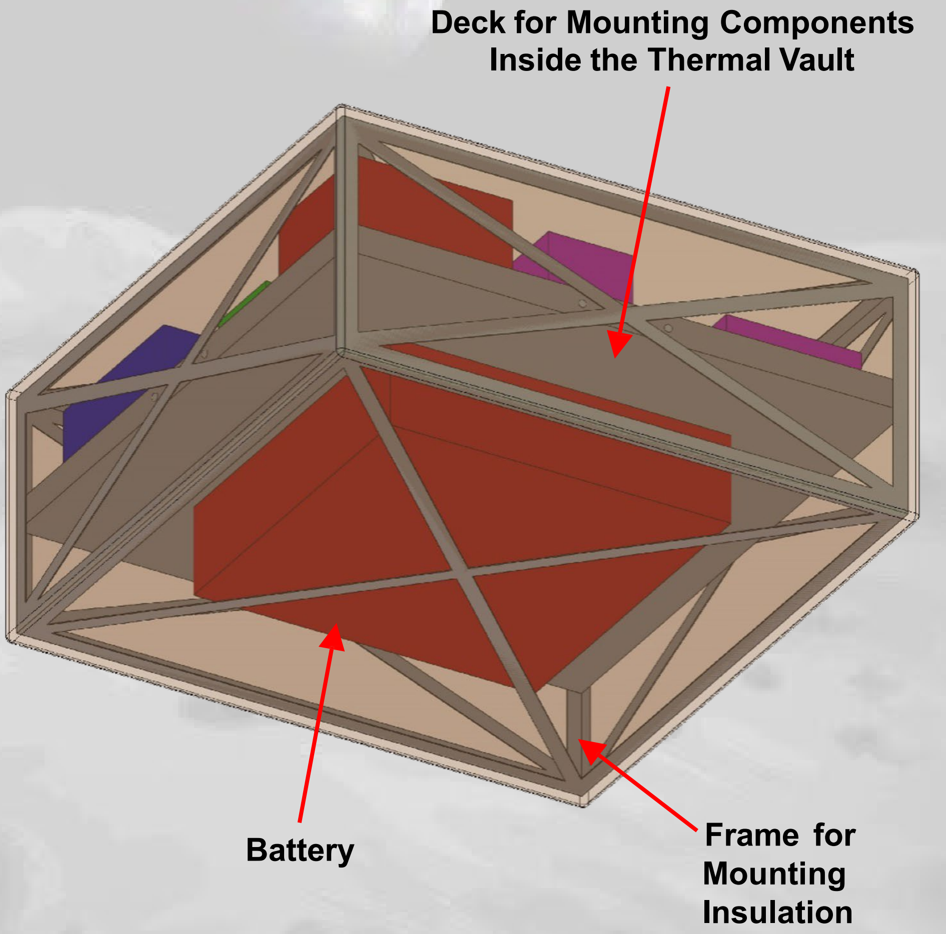


Lunar Night Lander Thermal Vault Concept



Science Lander Thermal Vault Components





Thermal Vault Operation on the Surface at Night

Sky Temperature 4 K

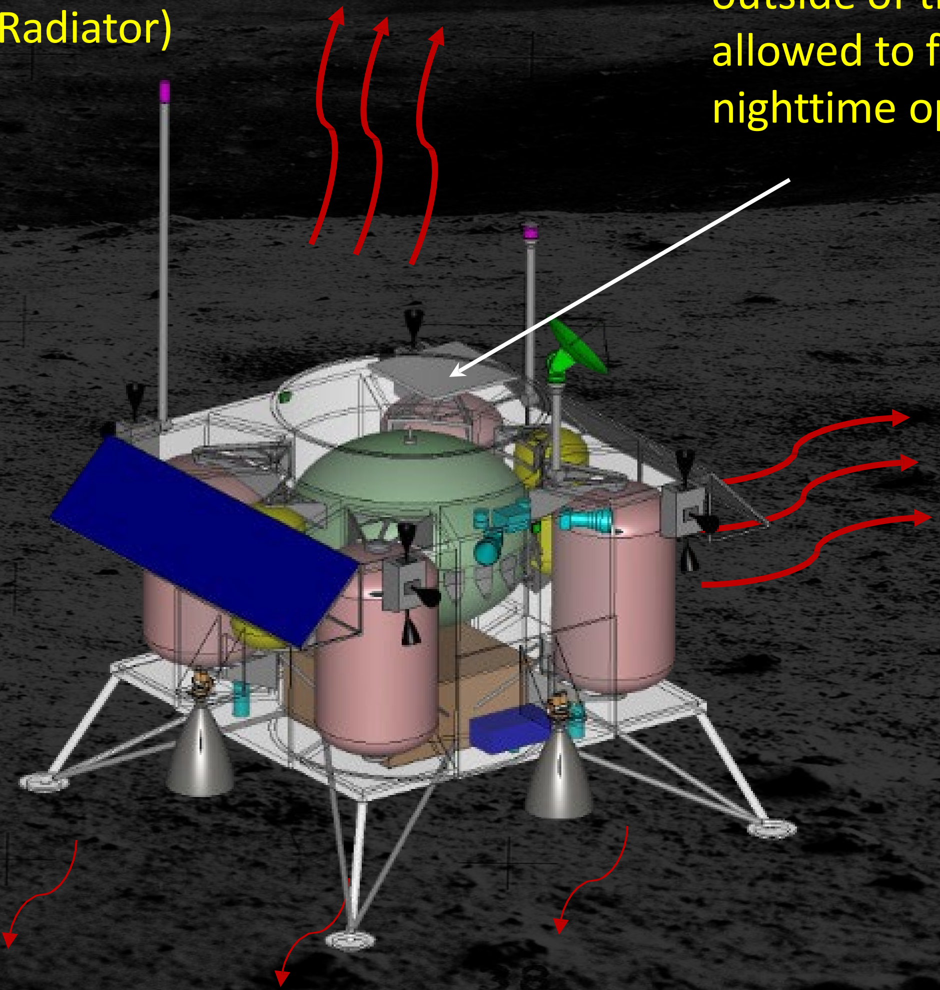
Effective Sink Temperature: 64 K (Thermal Vault) 33 K (Radiator)

View to Sky: 0.5

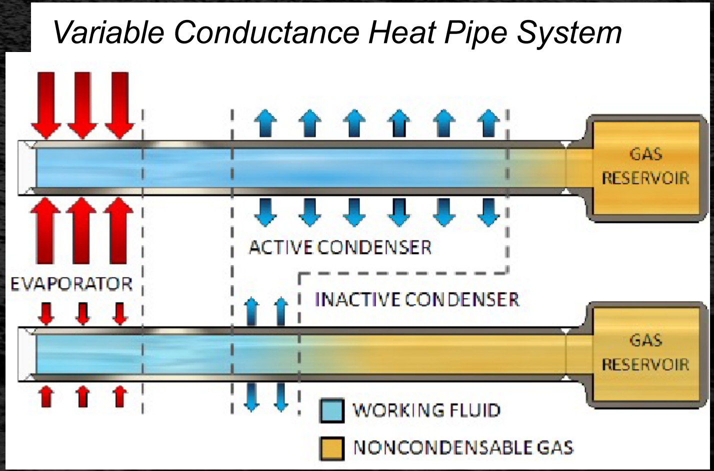
Surface: 80K

Radiator is used for operation during daytime only. It is located outside of the thermal vault and allowed to freeze during nighttime operation.

Radiator is automatically 'switched off' by use of variable conductance heat pipes

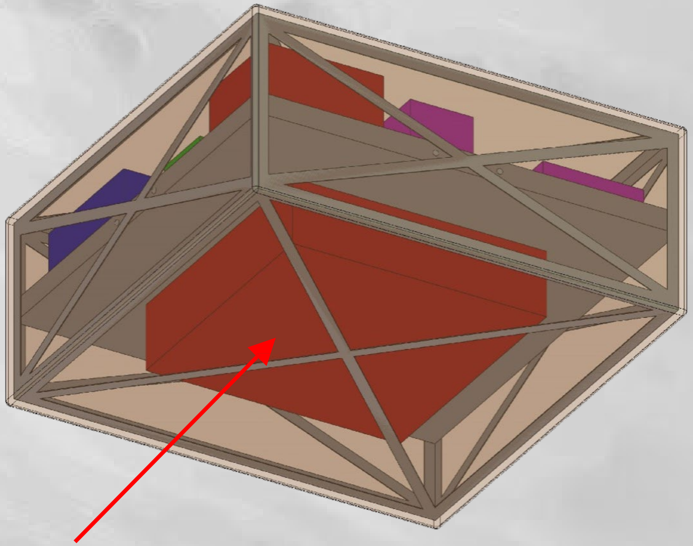


View to Surface: 0.5



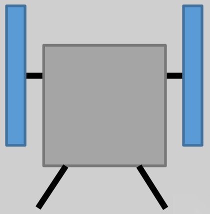
Battery Design

- Sizing requirements driven by Night Operations
- Lunar Night is 354 hours long
  - Operational nighttime power is ~40 W, EPS losses total ~6 W
    - Assume battery-tied bus to remove battery discharge unit efficiency drop
    - Assume all Terma cards are disconnected during night (no parasitic consumption), except 2x PDUs
  - Use 90% DoD to reduce battery mass
    - (only expect 125 charge/discharge cycles, so this is acceptable)
- Li-ion Battery
  - 1568 cells in 8s-196p configuration, ~20 kWh capacity
    - 1 spare string
  - LG 18650 MJ1 cells used
  - 28 V nominal, assume loads can operate over voltage range
  - Battery pack is 28x28 cells across, 2 cells high
  - Specific energy of ~200 Whr/kg

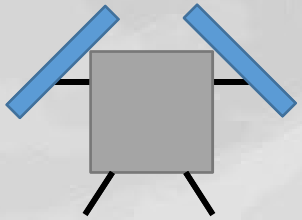


Solar Array Angle Trade

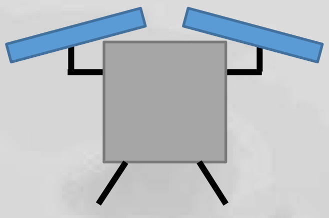
- Steep angle (90° tilt)
  – Battery power is used during the noon hours as array output drops
  – Battery won't be fully charged at end of day without larger array; increases area by at least 1 m^2 and mass by 2.5 kg (per wing)

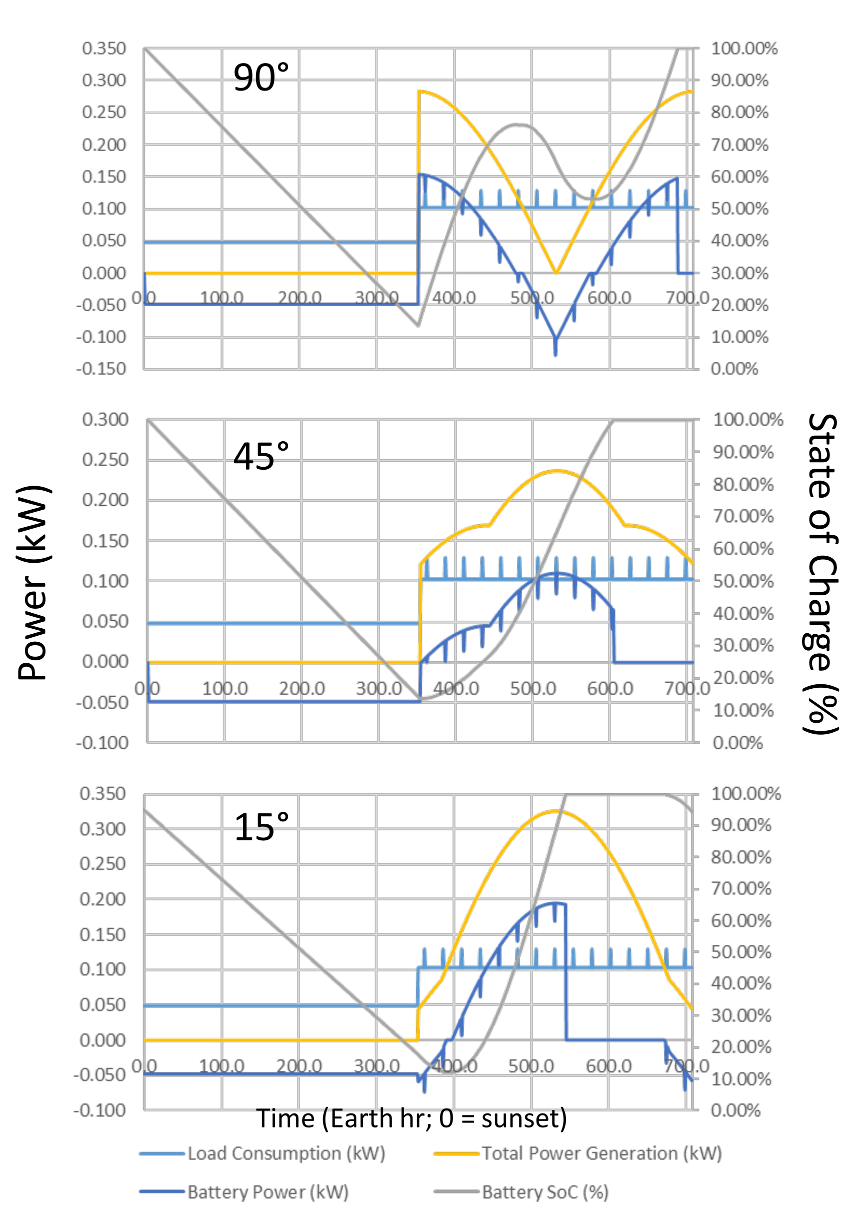


✓ Medium angle (45° tilt)
  – No battery power required over entire insolation period



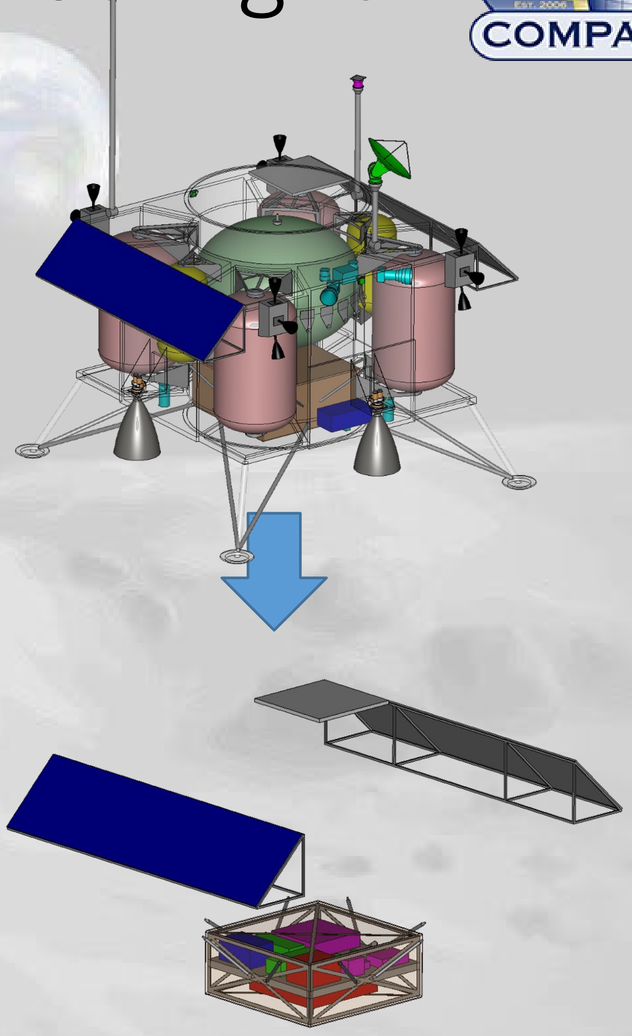
- Shallow angle (15° tilt)
  – Batteries continue to discharge past dawn, begin dusk at <99% SoC
  – Can shrink array size, but requires larger battery to satisfy max DoD; increases mass by at least 10 kg





Mass Added for ~40W Operations at Night

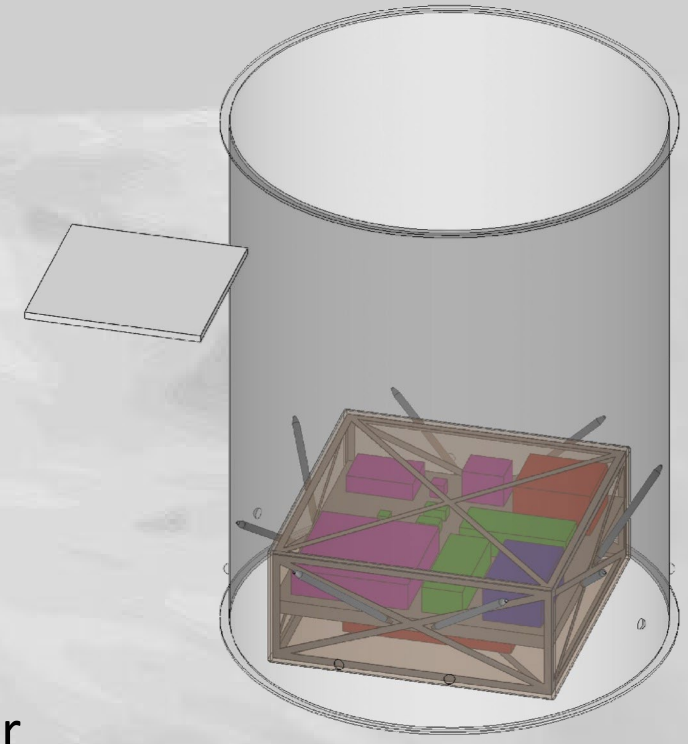
- Assuming a Science mass ~100 kg, many currently planned CLPS landers could perform the mission during daylight
- ***But*** the Additional equipment needed for a lunar night
  - ***140 kg*** –Night-Time Electrical Power
    - Added Batteries, PMAD used for payload, Increased solar array area to charge batteries
  - ***23 kg*** – Thermal Vault Thermal control
    - heaters, radiators, heat pipes
  - ***34 kg*** – Thermal vault and secondary structure
    - brackets, booms, etc.
  - ***18 kg*** – Command & Data Handling
    - Added science computer, storage, etc. into Vault
  - ***~280 kg – Total Additions***
    - (incl 30% growth) more mass delivered for night-time
- ***This would change the class of the CLPS lander from the 100 kg lander to the ~500 kg range landers***



Night-time Equipment Added to Lander

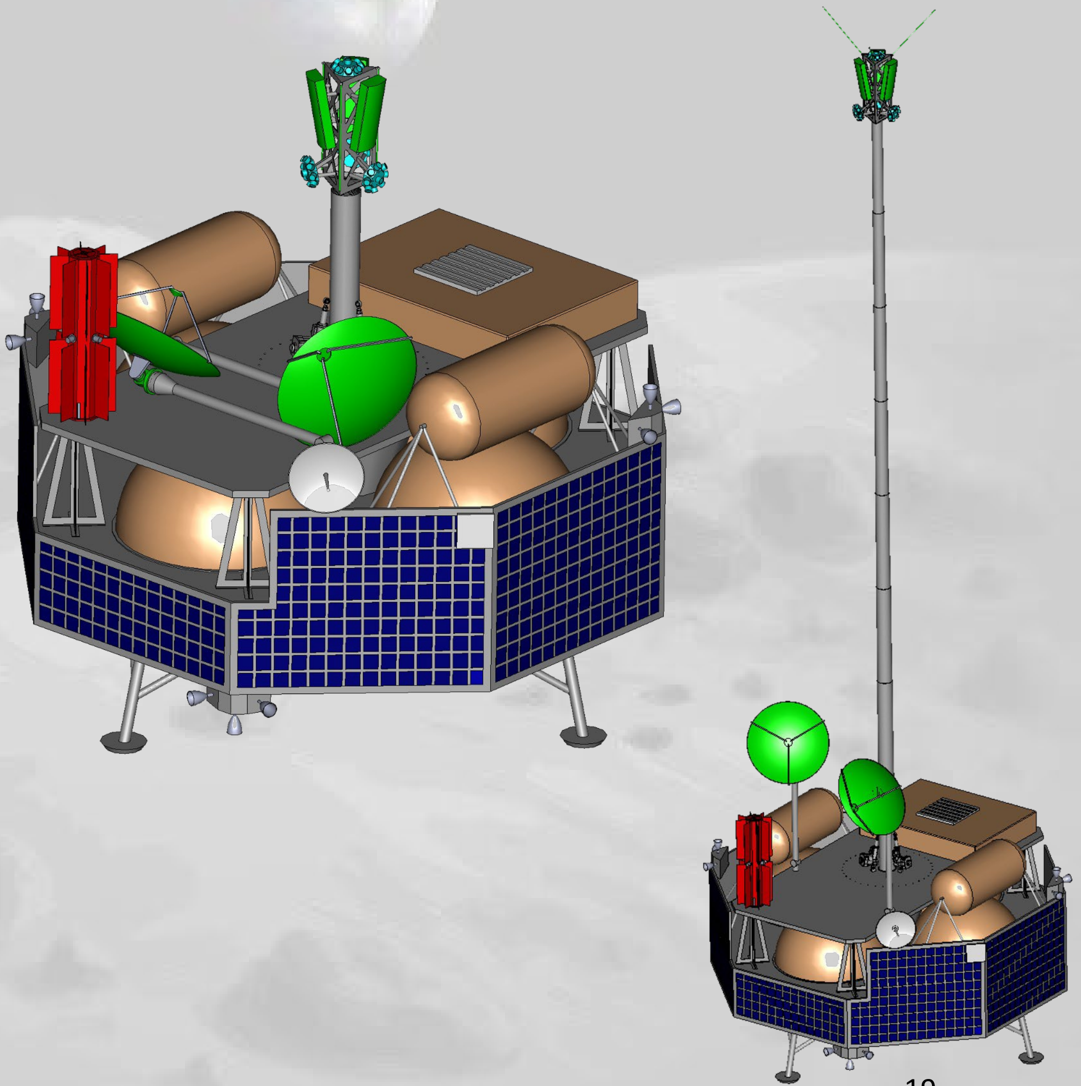
Lessons Learned

- A solar/battery design with a thermal ‘vault’ to minimize Lunar night heat leak was developed
  - Kept the night-time instruments operating as well as the science electronics alive
  - Have ~ 40W of night-time power operations – only leak ~ 15Wth of heat – have thermal margin in the design
- The waste heat from the science electronics and C&DH was sufficient to keep the thermal vault warm without the need for RHUs
- Rule of thumb
  - For every 1 W of 2 weeks Lunar Overnight Power / Thermal Protection you need ~7 kg of support equipment
- CLPS Class Lander
  - Roughly 400 kg of payload and night-time support mass is needed for each lander



Impact of Radioisotope Power

- *Use of Radioisotope power systems can greatly increase the night-time power / thermal capabilities for the same heavy CLPS lander as the previous example: **usable payload instead of large battery pack / thermal vault***
- Next Generation RTG ~ 60 kg and provides ~170-190 W of power for 13 yrs (dependent on environment)
  - ~ 200Wth heat easily available for keeping components warm
  - Up to 3500 Wth heat could be used (keep rovers warm during the night?)
- Radioisotope Powered CLPS class lander example
  - Mission: Lunar Surface Relay to provide
    - 5G, UHF, and Navigation for lunar surface users
    - Trunk of up to 10 video streams(8 hrs every 24 hrs, day & night), communications, controls, science, housekeeping
  - Heavy Class CLPS lander (~500 kg payload)
  - Power: Single, Next-generation RTG ~ 170We day and ~190We night power
    - Batteries for peak video power links
  - Thermal: Variable Conductance Heat Pipes take waste heat from RTG and heat Relay payload box during night operations
- Payload Mass ~ 475 kg



Sample Compass Customers

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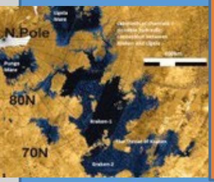
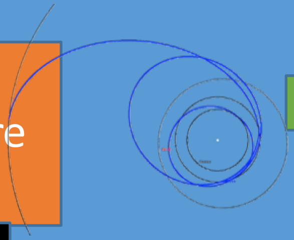
Compass Design Process

Establishing the Study Definition

Customer meetings: FOMS, Requirements



Mission architecture studies



Configuration: Initial cut

Mass Properties: Initial cut

Prework

Gather the team

Improve tools

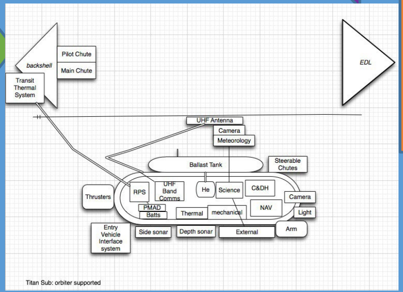
Establish the schedule

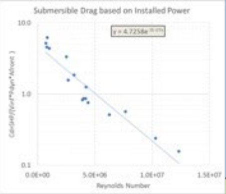
Design Study with Concurrent Team

Initial cut at design

Brainstorming

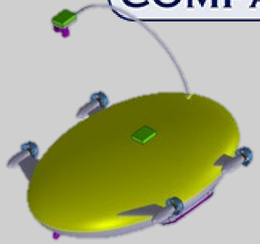
Iteration and design improvements





Final design meeting customer requirements

Post Work



Final design products

Final design presentation

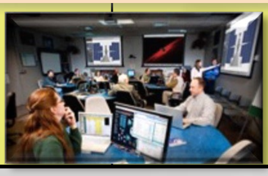
Final report generation

Customer Meeting

Mission Analysis Pre-study work

Pre-Work

Design Sessions



Post-Work

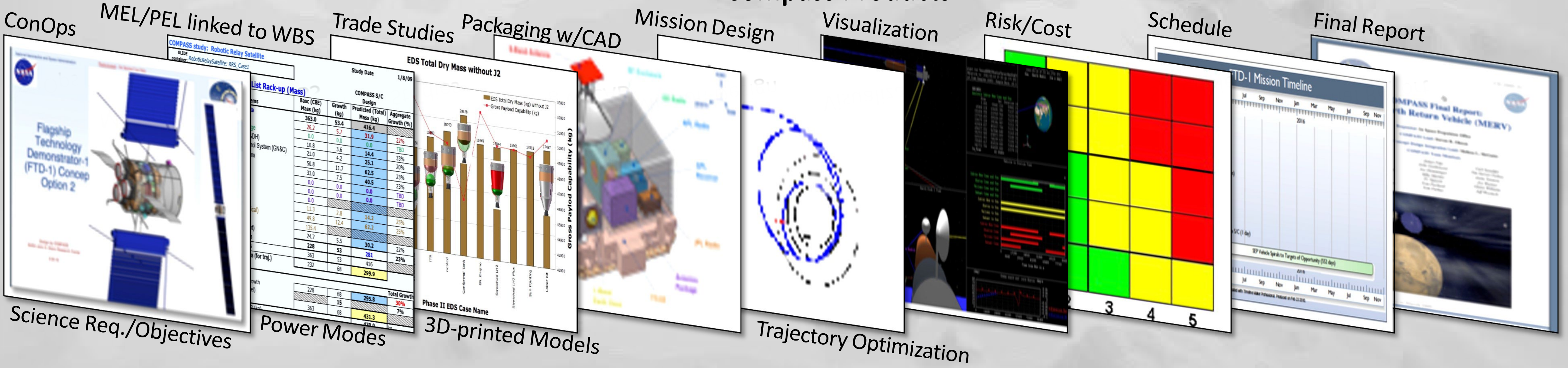
Draft Charts to Customer

Week 1 | Week 2 | Week 3 | Week 4 | Week 5 | Week 6

Compass Design Products

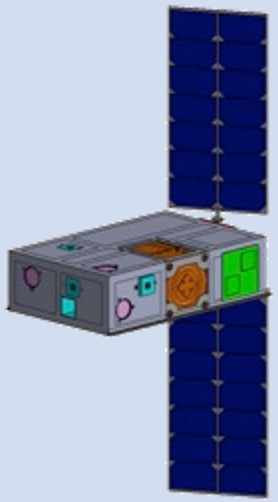
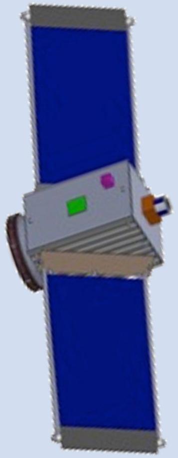
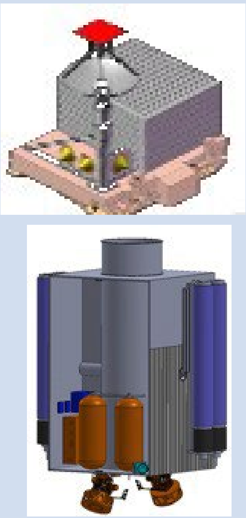
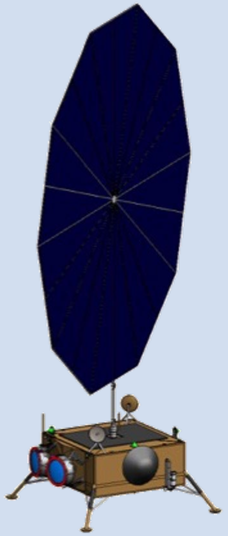
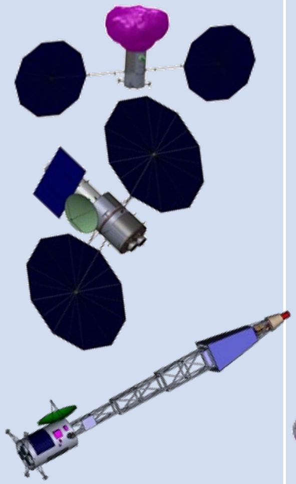
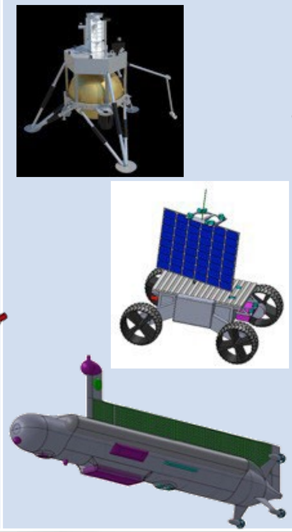
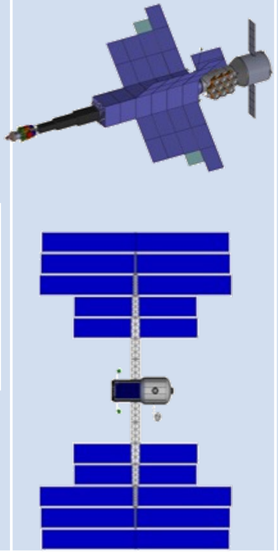
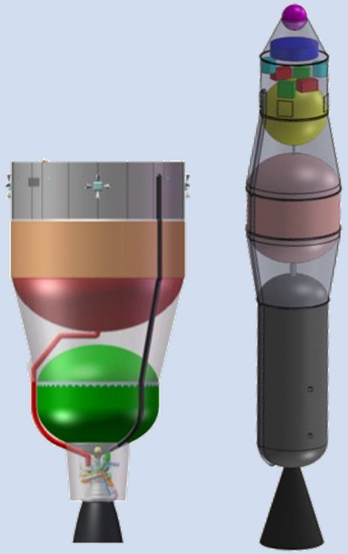
- Compass Products/Analyses are tailored to support the customer
  - A large suite of Compass products are available for selection
  - The customer establishes the depth, fidelity, and scope of the study and products, prior to study kickoff
- Compass Products have supported proposals, implementation/assessment of technologies, Design Reference Missions, and project reviews per NPR 7123.1A (ex: MCRs & SRRs)

Compass Products



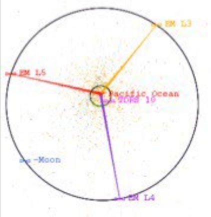
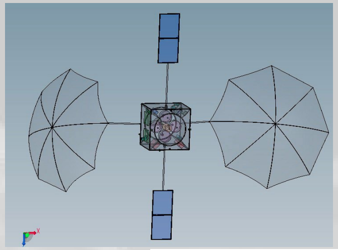
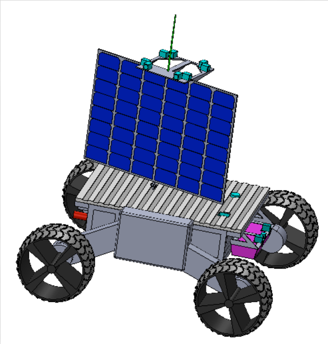
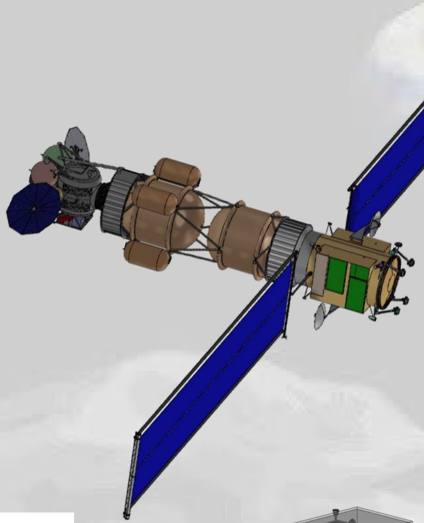
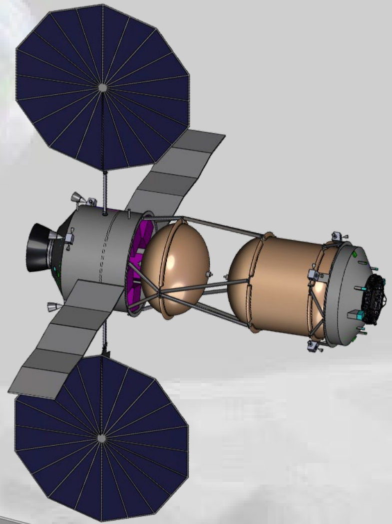
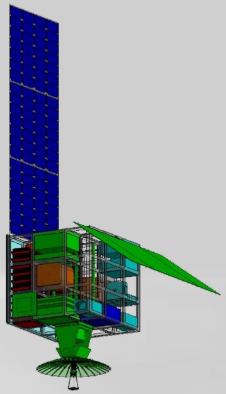
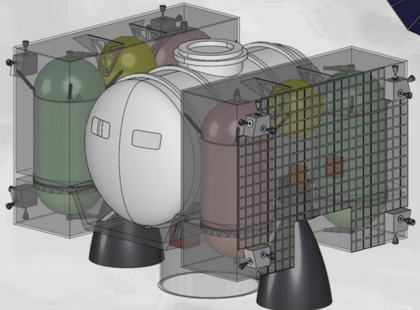
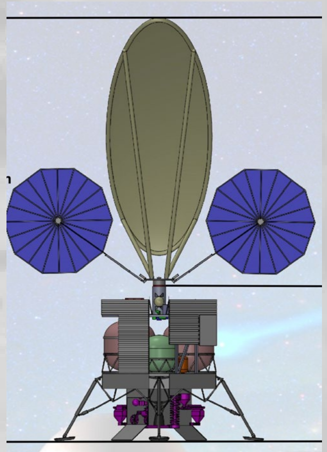
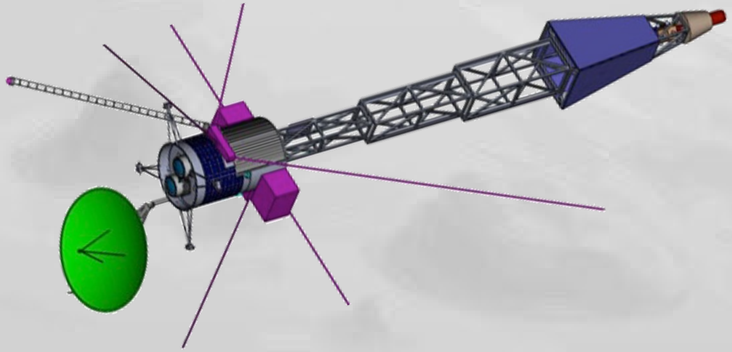
Design Experience

- Compass has produced more than 200 designs
  - Designs span in size from cubesats to ISS-scale deep space human exploration spacecraft
  - Destinations include all the planets, many moons, small bodies and their surfaces
  - Mission Types include technology demonstrator missions, to science missions, to design reference missions (DRMs)

Microsats	Smallsats	Technology Demonstrators	Sample Return	Science Sats	Landers, Rovers, Extraterrestrial Submarines	Crewed	Launchers/Stages
							

Compass CisLunar Space Experience

- Cis-Lunar Orbiters
  - Cislunar relays, tankers, depots, crewed vehicles (pre-Gateway and Power and Propulsion Element), cubesats
- Lunar Surface
  - Crew landers/ascent vehicles, rovers (big and small),Large solar and Fission Power systems, ISRU
- Many Fission systems:
  - Nuclear Electric Propulsion
  - Fission Surface Systems

Sample Customer Feedback

"Compared to other government and contractor studies, the Compass team's process provided results at a greatly reduced cost and time."
- Crane Division
Naval Surface Warfare Center

NASA Systems Engineering Award

"The team followed a well-structured systems engineering process ensuring that the customer needs and expectations were met throughout the process."
- Exploration Missions and Systems Office, NASA Johnson Space Center

Space Flight Awareness Team Award

"With the Compass team, the time-savings is multiplied and greatly enhances ATK competitiveness."
- ATK Space Systems

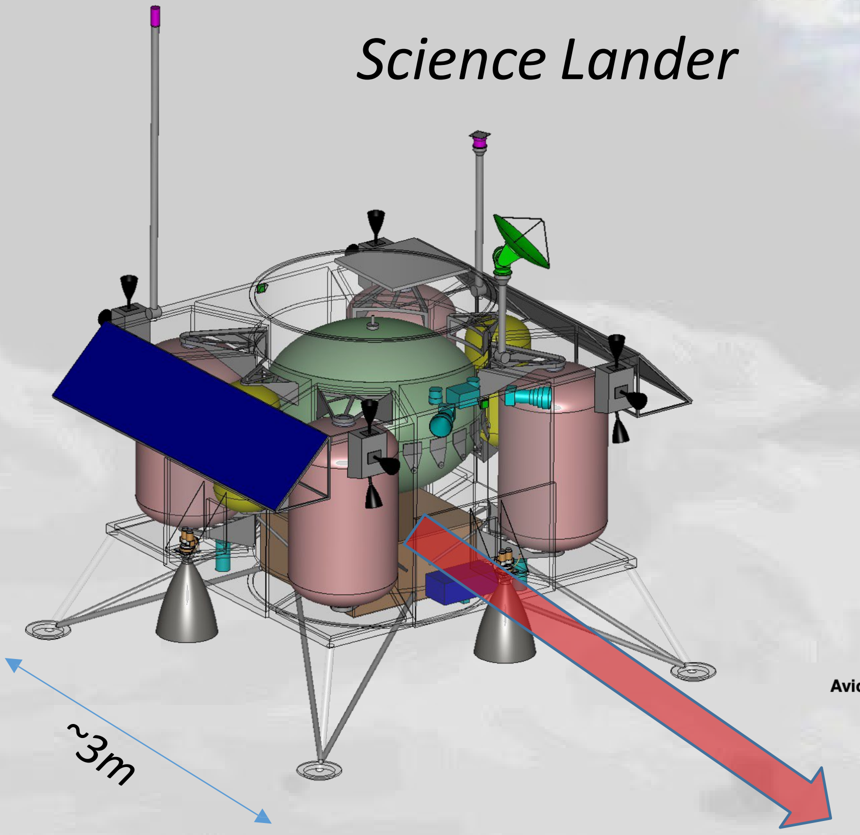
NASA Honor Award:
Group Achievement Award

Low Overnight Power Lunar Science Lander

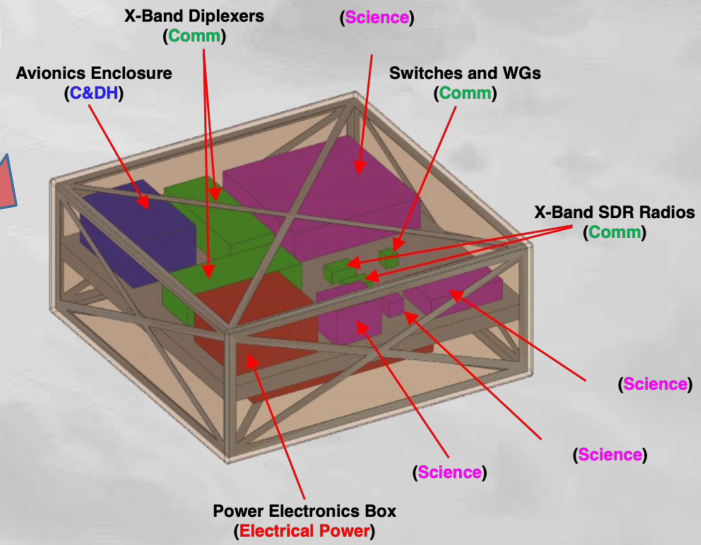
- **Generic Science lander:**
  - ~ 100 kg science payload Day & Night-time operations
  - ~ 40 We night-time power for data collection/storage
- **Science:** 24/7 base science operations with surface and subsurface components
- **Thermal:** Innovative 'Thermal Vault' design to minimize night-time heat leaks and keep science/C&DH/Comms electronics warm (>-40°C) during lunar night, 25 layers MLI, Variable conductance heat pipes, minimized cabling leaks, low conductivity struts to hold thermal vault. Night-time electronics waste heat sufficient to keep vault warm, NO RHUs needed
- **Power:** Fixed East/West 45° solar arrays, ~ 100 kg of Li-ion batteries to keep electronics warm
- **Structures:** low thermal conductivity struts for thermal vault
- **C&DH:** two computers, one inside thermal vault, 128 GB of storage for science
- **Comms:** X-band comms, 1 hr daily to DSN

Science Lander

Inert Mass ~ 1500 kg
Wet Mass ~ 4000 kg



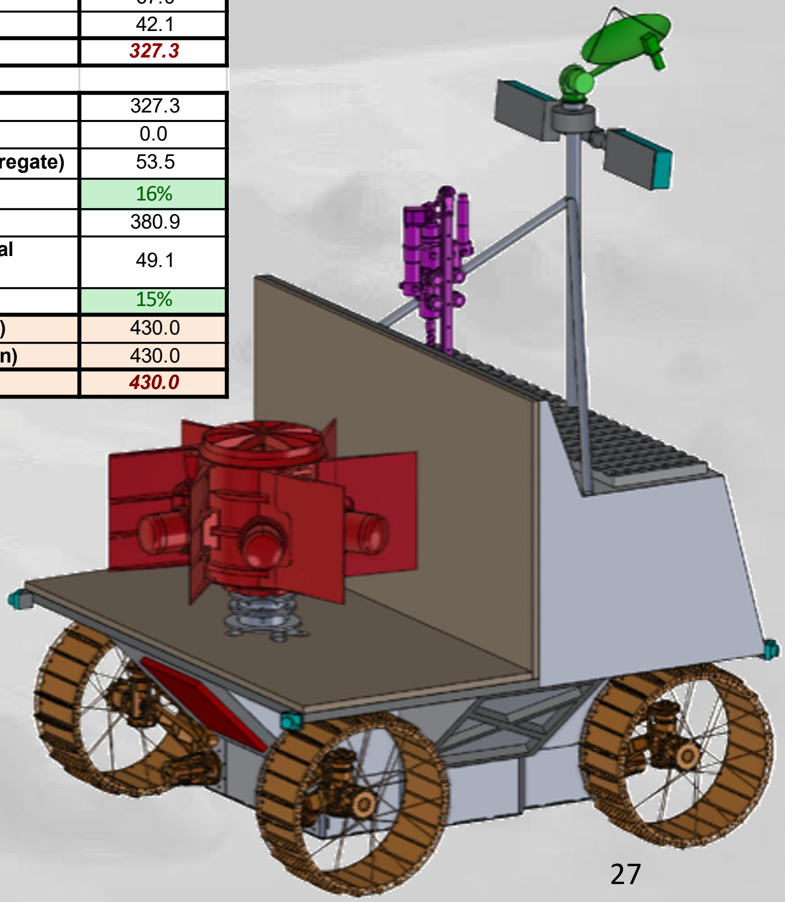
Thermal Vault for Lunar Night operations



DRPS Rover for PSRs: Executive Summary

- Overview: Rover will demonstrate a Dynamic Radioisotope Power System (DRPS) while providing long duration, 18 month exploration of Permanently Shadowed Regions on the south pole of the moon
- Mission:
  - Launch, lander, rover equipment/science using Astrobotics/VIPER solar rover, assume that reuse of VIPER components will reduce costs
  - Install DRPS vertically through fairing door using beam/crane, switch to rover installed controller, cool in fairing
- Science: Drill and three spectrometers, search for water
  - DRPS will heat up areas behind the rover in DRPS so science focus needs to stay in front of thermally shielded part of rover
  - Additional TBD science instrument also carried
- Power: Representative ~ 330We, 6 GPHS DRPS, batteries for peak loads (roving and drilling)
- Mobility: same wheel/motors as Viper ~ 10cm/s avg speed, up to 15° slope
- Thermal: Adiabatic walls and struts to isolate waste heat from DRPS, Rover bus insulated and heated using avionics waste heat, louvered radiator during sunlit operations
- Comms: Ka band (high gain: 250 kbps and omni) up to Gateway for relay with earth, option for DTE when in sight
- C&DH: Control of all mobility/science, 1 TB data storage, performs waypoint driving based on earth commands
- AD&CS: IMU, startracker, Gateway tracking, surface recognition
- Structures: Al bus with low conductivity materials to keep heat in rover, 5 g launch loads

MEL Summary: Case 1_DRPS_DRM_Rover CD-2021-182	Rover
Main Subsystems	**Basic Mass (kg)**
Radioisotope Power	96.4
Attitude Determination and Control	4.7
Command & Data Handling	18.4
Communications and Tracking	10.7
Electrical Power Subsystem	13.4
Thermal Control (Non-Propellant)	34.8
Science	40.0
Mobility	67.0
Structures and Mechanisms	42.1
Element Total	***327.3***
Element Dry Mass (no prop,consum)	327.3
Element Propellant	0.0
Element Mass Growth Allowance (Aggregate)	53.5
MGA as a %'age	16%
Predicted Mass (Basic + MGA)	380.9
Recommended Mass Margin (Additional System Level Growth) 15%	49.1
Margin as a %'age	15%
Element Dry Mass (Basic+MGA+Margin)	430.0
Element Inert Mass (Basic+MGA+Margin)	430.0
Total Wet Mass (Allowable Mass)	***430.0***



AmDRPS Rover for PSRs: Executive Summary

- Overview: A comparison design using a conceptual Am241 Dynamic Radioisotope Power System (DRPS) which provides long duration, 18 month exploration of Permanently Shadowed Regions on the south pole of the moon
  - This 216WDC Am241 DRPS weighs about 110 kgs. Operating next to the thermal barrier, the AmDRPS produces 213 We, allowing conops of 8 hours driving, 1 hour science drilling, and 14.25 hours recharge in standby.
  - This AmDRPS rover can spend long durations in permanently shadowed craters and could traverse >100km in 18 months
- Mission:
  - Launch, lander, rover equipment/science using Astrobotics/VIPER solar rover, assume that reuse of VIPER components will reduce costs
  - Install AmDRPS vertically through fairing door using beam/crane, switch to rover installed controller, cool in fairing
- Science: Drill and three spectrometers, search for water
  - DRPS will heat up areas behind the rover in AmDRPS so science focus needs to stay in front of thermally shielded part of rover
  - Additional TBD science instrument carried (same assumption as PuDRPS design)
- Power: Representative 216We (213We accounting for thermal barrier), 4 ELHS heat sources, 6 DRPS Stirlings, batteries for peak loads (roving and drilling)
- Mobility: same wheel/motors as VIPER ~ 10cm/s avg speed, up to 15° slope
- Thermal: Adiabatic walls and struts to isolate waste heat from DRPS, Rover bus insulated and heated using avionics waste heat, louvered radiator during sunlit operations
- Comms: Ka band (high gain: 250 kbps and omni) up to Gateway for relay with earth, option for DTE when in sight
- C&DH: Control of all mobility/science, 1 TB data storage, performs waypoint driving based on earth commands
- AD&CS: IMU, startracker, Gateway tracking, surface recognition
- Structures: Al bus with low conductivity materials to keep heat in rover, 5 g launch loads

MEL Summary: Case 3_AmDRPS_DRM_Rover CD-2021-182	Rover
Main Subsystems	**Basic Mass (kg)**
Radioisotope Power	109.7
Attitude Determination and Control	4.7
Command & Data Handling	18.4
Communications and Tracking	10.7
Electrical Power Subsystem	20.0
Thermal Control (Non-Propellant)	34.8
Science	40.0
Mobility	67.0
Structures and Mechanisms	42.7
Element Total	***347.8***
Element Dry Mass (no prop,consum)	347.8
Element Propellant	0.0
Element Mass Growth Allowance (Aggregate)	58.0
MGA as a %'age	17%
Predicted Mass (Basic + MGA)	405.8
Recommended Mass Margin (Additional System Level Growth) 15%	52.2
Margin as a %'age	15%
Element Dry Mass (Basic+MGA+Margin)	458.0